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Observability of Early Evolutionary Phases of Galaxies at mm Wavelengths

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Abstract

Several lines of evidence and theoretical arguments suggest that a large fraction of starlight is absorbed by interstellar dust and re-radiated at far-IR wavelengths, particularly during early evolutionary phases of early type galaxies, which may even, under some circumstances, experience an optically thick phase. Therefore far-IR to mm observations are crucial to understand the galaxy evolution. The strong K-correction makes surveys at mm wavelengths ideally suited for studying high-z galaxies. The broad redshift range covered by mm surveys at sub-mJy flux limits offers a good chance for gaining important information also on the geometry of the Universe.

1. Introduction

The IRAS survey has clearly demonstrated the crucial role of dust in shaping the spectral energy distribution (SED) of galaxies. A direct comparison of their local luminosity functions in the optical and in the far-IR shows that, locally, about 30% of starlight is reprocessed by dust.

It is very likely that this fraction was higher in the past, when the star formation activity was more intense and also early type galaxies possessed a plentyful interstellar medium, which might have been metal enriched on a very short timescale, the lifetime of the first generation of massive stars.

Thus, the observational study of evolution of dust emission in galaxies is crucial to understand the evolution of galaxies themselves.

2. Luminosity Evolution, Dust Absorption and Far-IR/mm Emission

A useful scheme for modelling the evolution of galaxies relies on the consideration of two extreme patterns (Sandage 1986): on one side, disk galaxies, characterized by dissipational collapse, with slow gas depletion, i.e. star formation rate (SFR) never much higher than today; on the other side, spheroidal galaxies thought to have used up most of their gas to form stars in a time short compared with the collapse time, i.e. with a spectacularly large initial SFR. The evolution of galaxies of different Hubble types can then be modelled as a suitable combination of the two basic components.

This scheme is certainly oversimplified in many respects; in particular, it does not allow for important facts such as merging, interactions, star formation induced by nuclear activity, and so on. Still, it may be useful to sketch out some of the chief features.

Our approach (Mazzei et al. 1992, 1994) exploits chemical and photometric evolution models of stellar populations, complemented by allowing for the effect of dust. Simple assumptions are adopted for the dust component, namely: the dust to gas ratio is proportional to the metallicity (i.e. a constant fraction of metals is locked up in dust grains); stars and dust are well mixed; the "standard" grain model (Mathis et al. 1977; Draine and Lee 1984), including a power law grain size distribution, holds at any time.

If indeed the metallicity and the star formation rate in *galactic disks* did not vary much throughout their lifetime, their SED too remained essentially unchanged, except for optical colours being somewhat bluer and the dust being somewhat warmer during the early phases (Mazzei et al. 1992).

On the contrary, dramatic far-IR evolution is expected for early-type galaxies due to the fast (exponential with a timescale of a few Gyr) decrease of the SFR with increasing galactic age. Their bolometric luminosity increases by a substantial factor with decreasing galactic age, T (a factor $\simeq 10$ from $T = 15\,\text{Gyr}$ to $T = 2\,\text{Gyr}$). Moreover, the far-IR to optical luminosity ratio increases from local values $\lesssim$,10^{-2} (Mazzei and De Zotti 1994a) to $\simeq 1$ or even $\gg 1$ at early times. On the whole, the far-IR luminosity of early type galaxies may have increased by about three orders of magnitude (if the effect of merging may be ignored), a luminosity evolution rate more extreme than even that quoted for optically selected quasars.

Under the above assumptions for dust properties, a key parameter in determining the evolution of the SED of early type galaxies, is the gas consumption rate: in the case of a fast conversion of gas into stars, the far-IR emission is never dominant; but if the gas depletion is slower, the galaxy may experience a prolonged opaque phase, with most of the luminosity emitted in the far-IR (Mazzei and De Zotti 1996).

In any case, *a substantial dust emission is expected during early evolutionary phases of all galaxies.*

2.1 Are primeval galaxies heavily obscured?

As noted above, under some circumstances, galaxies which are in the processes of transforming into stars a large fraction of their mass in a relatively short time (the conventional definition of primeval galaxies) may be heavily obscured by dust. We are unable to work out an a priori estimate of how frequently this may occur.

However, as shown by Franceschini et al. (1994), under the assumption that, during the phases of intense star formation, most of the optical radiation was absorbed by dust and reradiated in the far-IR, a consistent picture obtains in the framework of simple luminosity evolution models. In particular, we may account for: the remarkable lack of high redshift galaxies in optically selected samples down to $B \simeq 24$ (Colless et al. 1993; Cowie et al. 1991); the failure to detect Lyα emission in searches for primeval galaxies (e.g., Thompson et al. 1995); the deep $60\,\mu$m IRAS counts and, exploiting the far-IR/radio correlation for galaxies, most of the observed sub-mJy flattening of radio counts over a couple of decades in flux.

Also, contrary to recent claims (e.g. Thompson et al. 1995), predictions of models entailing strongly obscured primeval galaxies are not in conflict, but may even be supported by COBE data on the far-IR to mm background (cf. Fig. 1).

2.2 Direct Evidences of Large Amounts of Dust in High-z Sources

The observed spectral energy distribution of the ultraluminous object IRAS F10214+4724 (Rowan-Robinson et al. 1991; Lawrence et al. 1993), at $z \simeq 2.3$ is remarkably well fitted by a model for young (age $\lesssim$,$1\,\text{Gyr}$) spheroidal galaxies with strong dust extinction (Mazzei and De Zotti 1994b).

On the other hand, this source hosts an active nucleus which may well be the main energy source, as strongly suggested by the evidences of gravitational lensing (Eisenhardt et al. 1996). Indeed, Granato et al. (1996) obtain a good fit of its SED with the dusty torus model that fits the SEDs of both broad and narrow line AGNs in the framework of the unified model (Granato & Danese 1994). The diameter of the far-IR emitting dusty torus is, in their model, of $\simeq 2\,\text{kpc}$ (for $H_0 = 50$), corresponding to an angular size of $0''.3$.

Dust masses $\simeq 10^8$–$10^9\,m_\odot$ (suggesting gas masses of between 10^{10} and $10^{12}\,m_\odot$) are indicated by mm/sub-mm detections (Dunlop et al. 1994; Chini & Krügel 1994; Ivison 1995) of the high z radio galaxies 4C41.17 ($z = 3.8$), 53W002 ($z = 2.39$), and 8C1435+635 ($z = 4.26$); such dust masses are 1–2 orders of magnitude higher than found for nearby radio galaxies (Knapp et al. 1990; Knapp & Patten 1991).

Furthermore, evidences of vast reservoirs of dust at high z are provided by mm/sub-mm detections of a number of distant radio quiet QSOs (Andreani et al. 1993; Ivison 1995, and references therein); several high-z radio loud QSOs were also detected, but the observed mm fluxes could be accounted for by synchrotron emission.

As in the case of IRAS F10214+4724, the relative importance of the nucleus and of a possible gigantic burst of star formation in heating the dust is still unclear. A better determination of the effective dust temperature, that may soon be provided by ISO observations, will certainly be extremely helpful: dust temperatures exceeding $\simeq 60\,$K are probably difficult to explain with a starbust model. But for a firm assessment of the problem, we will probably need the sensitivity and the angular resolution of the large mm array which would allow an observational characterization of the structure and luminosity of both the torus and the starburst.

3. Flux vs Redshift at mm Wavelengths

The spectral energy distribution (SED) of galaxies during the early evolutionary phases, characterized by intense star formation activity, is likely to be qualitatively similar to that of the nearby starburst galaxy M 82, shown in Figure 2.

Above a few mm, the luminosity is dominated by radio emission. The study of this emission and of its evolution is an interesting problem *per se* since a better understanding of the relative contributions of synchrotron and free-free processes at these wavelengths would shed light on the properties of the magnetic field on one side and of HII regions on the other.

In the range $100\,\mu$m–1 mm, dust emission dominates and the continuum spectrum of star forming galaxies can be described by a power law of the form $L_\nu \propto \nu^\alpha$ with $\alpha \simeq 3.5$ (Franceschini and Andreani 1995; Chini et al. 1995), although the far-IR to optical luminosity ratio in the case of normal late type galaxies is substantially smaller than for M 82, consistent with the correlation between far-IR emission and star formation rate.

Then, as we observe at mm wavelengths galaxies at larger and larger redshifts, the K-correction works to rapidly increase the flux, as we move to higher and higher frequencies along a steeply increasing spectrum (Franceschini et al. 1991; Blain and Longair 1993). For steep enough spectral indices, the K-correction eventually overcomes the effect of increasing distance, so that, above some redshift z_m, the flux actually increases with distance.

In the absence of any luminosity evolution, if $\alpha = 3.5$ we have $z_m = 2$, 1.83, 1.60, 1.29, and 0.96 for $\Omega = 0$, 0.03, 0.1, 0.3, and 1, respectively (De Zotti et al. 1996).

The minimum, however, is shallow, so that it can hardly be exploited to determine the density parameter. On the other hand, the weak dependence of flux on distance implies a rather uniform distribution of sources over a broad redshift range (up to $z \simeq 10$, if galaxies were already present) thus offering a good chance of exploring the geometry of the universe, particularly once the photometric evolution of galaxies will be reasonably well understood.

4. Predictions for Deep Millimeter Surveys

Estimates have been attempted by Franceschini et al. (1991), Blain & Longair (1993, 1996), Mazzei et al. (1996), based on different evolution models.

Such estimates, however, are a very delicate exercise because they require large extrapolations with very limited observational constraints. The nearest counts on the far-IR side, the IRAS counts

at 60 μm, span a limited range of flux and are rather uncertain at the faint end. On one hand, the redshift survey by Ashby et al. (1996) of the deep IRAS field at the North ecliptic pole (Hacking & Houck 1987) has discovered that the counts may be significantly above average because of the presence of a large supercluster at $z = 0.088$. At the other hand, Gregorich et al. (1995), from a study of a set of deep IRAS fields covering a total area about three times larger than that of Hacking and Houck (1987) report faint counts about a factor of two higher (note, however, that the completeness limit adopted by Gregorich et al. (1995), $\simeq 50$ mJy, is only 2.5 times higher than the estimated rms confusion noise; there is thus a serious danger that counts are overestimated at the faint end because of source confusion).

Also, there is a considerable spread in the observed (1.3 mm/60 μm) flux ratios of galaxies (cf. Fig. 3), implying a correspondingly large uncertainty in the estimated local luminosity function of galaxies at mm wavelenghts; this uncertainty is strongly amplified by the extreme steepness of the counts.

From a theoretical point of view, there is a great deal of uncertainty on the physical processes governing galaxy formation and evolution. At one extreme there are models assuming that the comoving density of galaxies remained essentially constant after their formation, while they evolved in luminosity due to the ageing of stellar populations and the birth of new generations of stars (pure luminosity evolution). At the other extreme, according to some hierarchical clustering models, large galaxies are formed by coalescence of large numbers of smaller objects. The observed properties of both disk and spheroidal galaxies imply that extensive merging cannot have occurred in the last several billion years (cf. e.g. Franceschini et al. 1994); it must, therefore, have occurred at significant redshifts.

The faint end of expected counts may be strongly different in the two cases. Of course, models advocating extensive merging at $z \geq 1$–2 imply a sharp enhancement of the counts at faint flux densities (Blain and Longair 1993, 1996). The flux density at which such enhancement begins is model dependent and is sensitive to several unknown quantities such as the merging history, the star formation rate and the initial mass function during the merging process, the dust temperature. On the other hand, a sub-$L_\star$ galaxy with a dust temperature of 60 K, typical of galaxies with very intense star formation, at $z \geq 1$ has a flux density $< 10\,\mu$Jy at 1.3 mm.

All in all, the actual physical processes governing the formation and the early evolution of galaxies may be very complex and may depend on an impressive number of unknown or poorly known parameters: spectrum of primordial density perturbations, hydrodynamic processes in the primordial gas, merging rate, star formation rate, initial mass function, galactic winds, infall, interactions, dust properties, and so on. The observational contraints are still very poor. Hence, a direct observational study of these phases is essential.

If, as argued above, metal enrichment and condensation of metals into dust grains occurs very quickly in primeval galaxies, far-IR to mm observations will play a crucial role in this field. ISO and SCUBA offer excellent prospects; their data will certainly help very much to discriminate between different scenarios. On the other hand, the much better sensitivity of the large mm array is required to test the possibility of substantial merging at $z > 1$–2, as expected, in particular, in the framework of cold dark matter cosmologies (Kauffmann et al. 1993).

5. Conclusions

The emission from interstellar dust, which locally comprises $\simeq 30\%$ of the global bolometric luminosity of galaxies, is very likely to have been significantly larger during earlier evolutionary phases, when the (metal enriched) ISM was more abundant. Therefore observations of the dust emission are crucial to understand the galaxy evolution.

In the case of early type galaxies, very poor of dust and gas at present, the evolution in the far-IR/mm bands could have been very spectacular, to the point that during the first 1–2 Gyr of

their lifetime, most of their starlight could have been reprocessed by dust; this corresponds to an increase of the far-IR luminosity by more than three orders of magnitude.

A related issue is the primary power source of ultraluminous IRAS sources (and in particular IRAS F10214 + 4724) and of the very large far-IR/mm emission from some high-z radiogalaxies. From the far-IR luminosity and the available constraints on dust temperature it is concluded that the dust distribution in the most luminous sources has a size of at least several hundred parsecs ($H_0 = 50$). The planned large mm array might resolve these sources even if the far-IR emission comes from a dusty torus surrounding an active nucleus.

The very steep increase of spectra of galaxies with increasing frequency in the range few-mm to $\simeq 100\,\mu$m makes surveys at mm wavelengths exceptionally well suited for investigating the evolution of galaxies up to $z \simeq 10$. The very weak dependence of flux on distance for $z > 1$ implies a very uniform coverage of the full redshift range over which galaxies presumably exist; once the physics of the evolution is understood, this gives a good chance of investigating also the geometry of the universe.

It may be debated whether the large mm array is the appropriate instrument for surveys aimed at investigating the early evolutionary phases of galaxies. Indeed SCUBA is expected to be capable of following the evolution of dust emission from bright galaxies up to very high redshifts. On the other hand, substantially better sensitivity and spatial resolution than achievable with SCUBA may be necessary to investigate e.g. the process of extensive merging of small dusty clumps at $z \gtrsim$,1–2. Other methods, such as the study of absorption lines in the spectra of high-z quasars, may be heavily biased if the clumps are very dusty.

On the other hand, for such surveys a not too small field of view at $\simeq 1$ mm is essential.

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Captions

Fig. 1: contributions to the far-IR to mm background intensity predicted by two different models for galaxy evolution, compared with limits (Hauser 1995) and estimates (dotted lines, Puget et al. 1996) based on COBE data. The lower thin curve is a minimal contribution from normal galaxies, estimated assuming no evolution up to $z = 1$. The dashed line is a *merging* model, in which most galaxies form stars and build up at $z \simeq 1$. The thick continuous line is an evolution model at constant galaxy mass function (for more details on both models see Franceschini et al. 1995).

Fig. 2: observed continuum spectrum of M 82 from UV to radio wavelengths. Data are from Hughes et al. (1989) and references therein, Cohen and Volk (1989), Huang et al (1994) and references therein, Kennicut (1992).

Fig. 3: SEDs of galaxies observed at mm wavelengths by Chini et al. (1995), normalized to $60\,\mu$m fluxes.